W bosons, Drell-Yan pairs, and jets

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- RhicBos update
- New opportunities
  - Tests of k_T factorization (low-Q Drell-Yan process)
  - Hadronic decays of W bosons

Can the true behavior of $\Delta f_a(x, Q)$
(especially for sea partons)
be separated from
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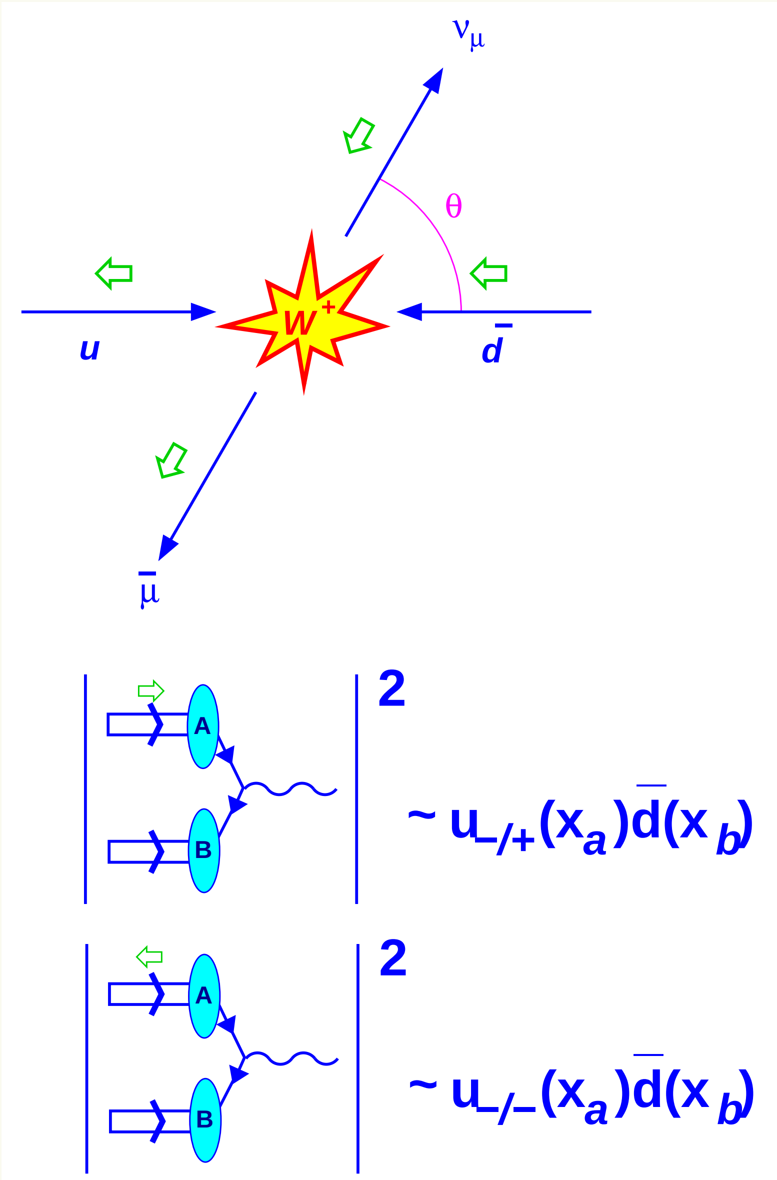
W boson production at RHIC!

- Complements and surpasses polarized SIDIS
- Probes the proton structure in a different kinematical range than the Tevatron and LHC

$W^{\pm}$-bosons as ideal polarimeters



$$A_L^{PV} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

At the Born level:

$$\frac{d\Delta_L \sigma(pp \xrightarrow{W^+} \ell^+ \nu_\ell X)}{dx_a dx_b d\cos\theta d\varphi} \propto$$
$$-\Delta u(x_a)\bar{d}(x_b)\,(1+\cos\theta)^2 +$$
$$+\Delta \bar{d}(x_a) u(x_b)\,(1-\cos\theta)^2$$

Spin asymmetries in $W^{\pm}$ production are sensitive to the flavor structure of the polarized quark sea

Classical signature: high-p_T charged leptons and $\not{E}_T$

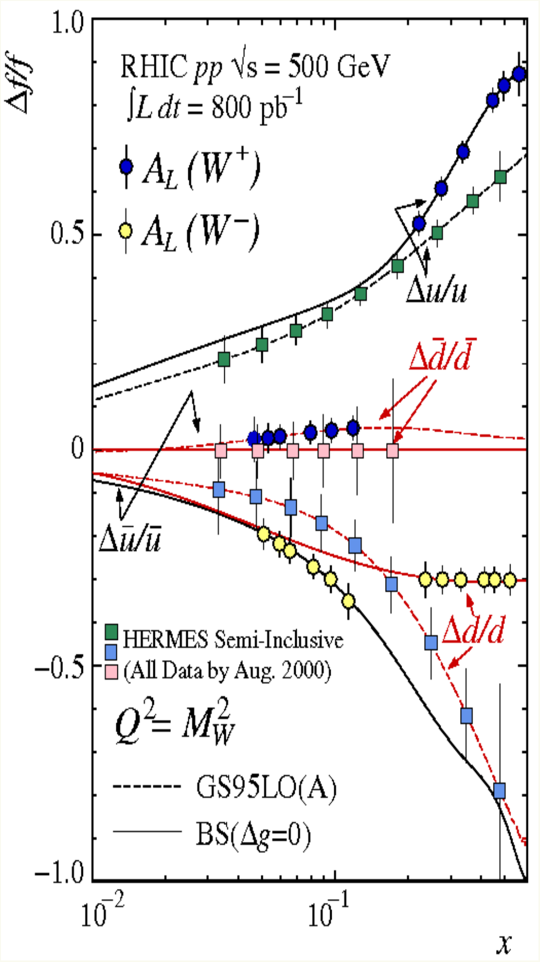
Leading order single-spin asymmetries for W boson rapidity distributions

$$A_L^{W^+}(y_W) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

$$= \begin{cases} -\Delta u(x_a)/u(x_a), & x_a \to 1 \\ \Delta\bar{d}(x_a)/\,\bar{d}(x_a), & x_b \to 1 \end{cases}$$

$$A_L^{W^-}(y_W) = \frac{-\Delta d(x_a)\bar{u}(x_b) + \Delta\bar{u}(x_a)d(x_b)}{d(x_a)\bar{u}(x_b) + \bar{u}(x_a)d(x_b)}$$

$$= \begin{cases} -\Delta d(x_a)/d(x_a), & x_a \to 1 \\ \Delta\bar{u}(x_a)/\bar{u}(x_a), & x_b \to 1 \end{cases}$$



- ❏ new Q range
- ❏ reliable theory (PQCD)
- ❏ guaranteed large asymmetries at $x \to 1$

Large lepton rapidities $(y_\ell \to y_\ell^{max})$

$$W^+ : \left(\frac{\Delta u(x)}{u(x)}\right)_{x\to 1} \qquad W^- : \left(\frac{\Delta d(x)}{d(x)}\right)_{x\to 1}$$

Behavior of valence PDFs at $x \to 1$ is predicted by constituent quark models

- ❐ Exact SU(6) symmetry [disfavored]:

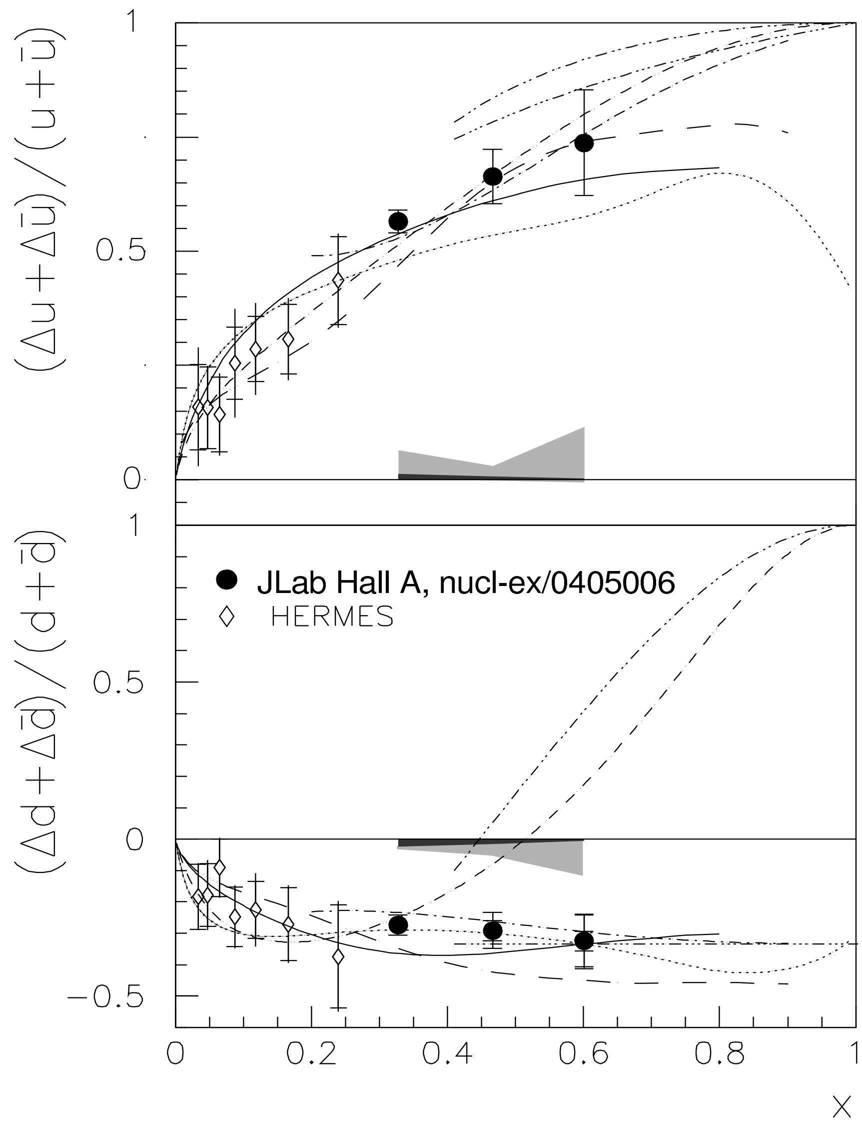
$$\frac{\Delta u(x)}{u(x)} \to \frac{2}{3}, \frac{\Delta d(x)}{d(x)} \to -\frac{1}{3}$$

- ❐ Hadron helicity conservation *(Farrar, Jackson;...)* [disfavored]

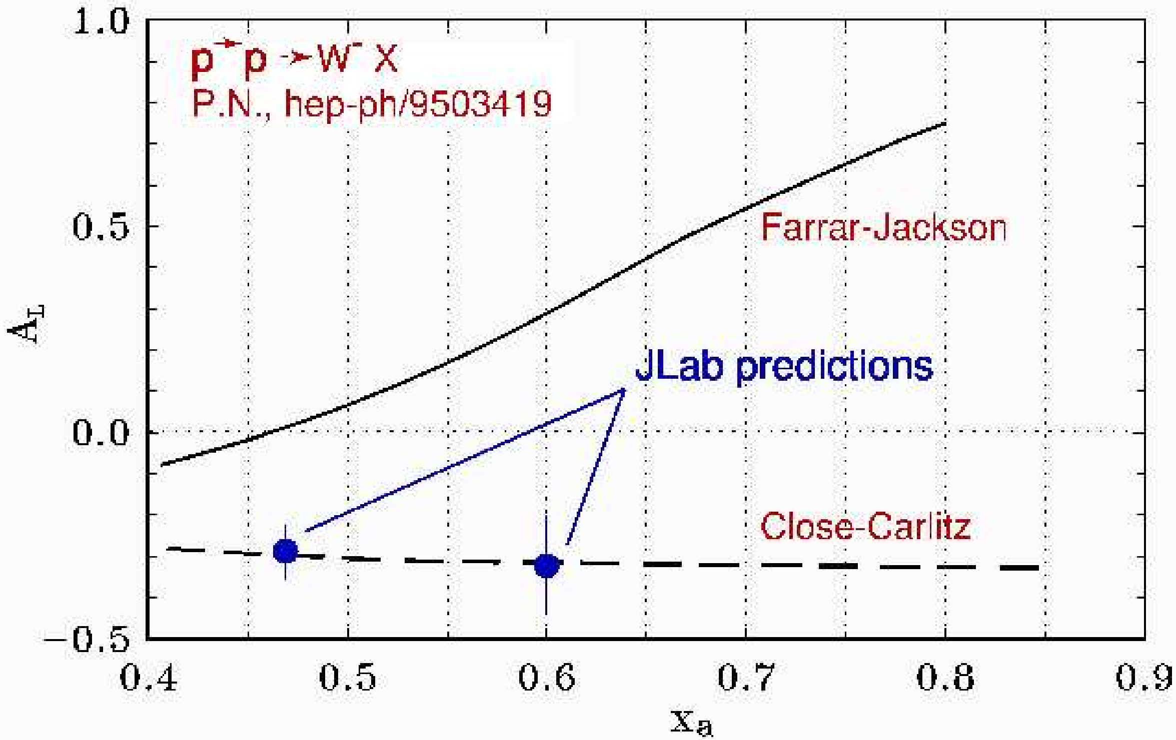
$$\frac{\Delta u(x)}{u(x)} \to 1, \frac{\Delta d(x)}{d(x)} \to 1$$

- ❐ Suppression of spin-1 diquarks *(Close; Carlitz;...)*

$$\frac{\Delta u(x)}{u(x)} \to 1, \frac{\Delta d(x)}{d(x)} \to -\frac{1}{3}$$



$A_L(y_W) \approx \Delta d(x)/d(x)$ in W^- boson production



- If the relationship $\Delta f_q(x, Q_0)/f_q(x, Q_0) \approx$ const for $x > x_0$ holds at some Q_0,
- and the valence PDFs dominate,

then this relationship holds at all Q [helicity conservation in PQCD radiation off valence quarks]

Beyond the leading order

A realistic model must account for

- QCD radiative corrections
- boson decay effects
  - $d\sigma/dy_W$ is not known; must look at $d\sigma/dy_e$
- detector acceptance

RhicBos: resummation program for polarized $W^{\pm}$, Z^0, and γ^* production

(P. N., C.-P. Yuan, Nucl. Phys. B666, 3 (2003);
Nucl. Phys. B666, 35 (2003))

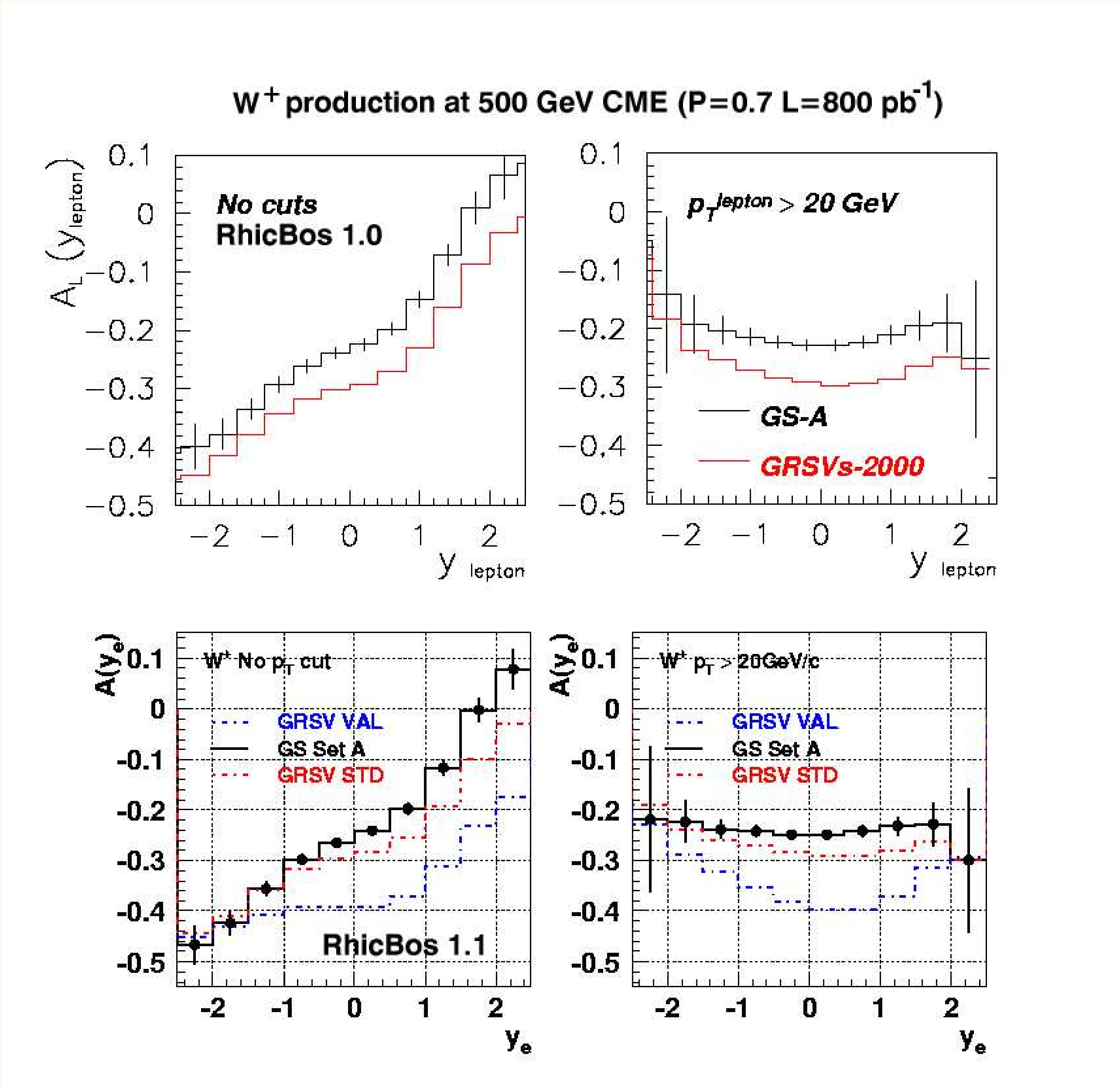
- Monte-Carlo integrator with resummation of soft gluons at partial NNLO (NNLL) accuracy
- effects of boson's width and decay, electroweak corrections
- unpolarized, single-spin, and double-spin cross sections
- lepton distributions for realistic acceptance

RhicBos: 2005 study *(B. Surrow et al.)*

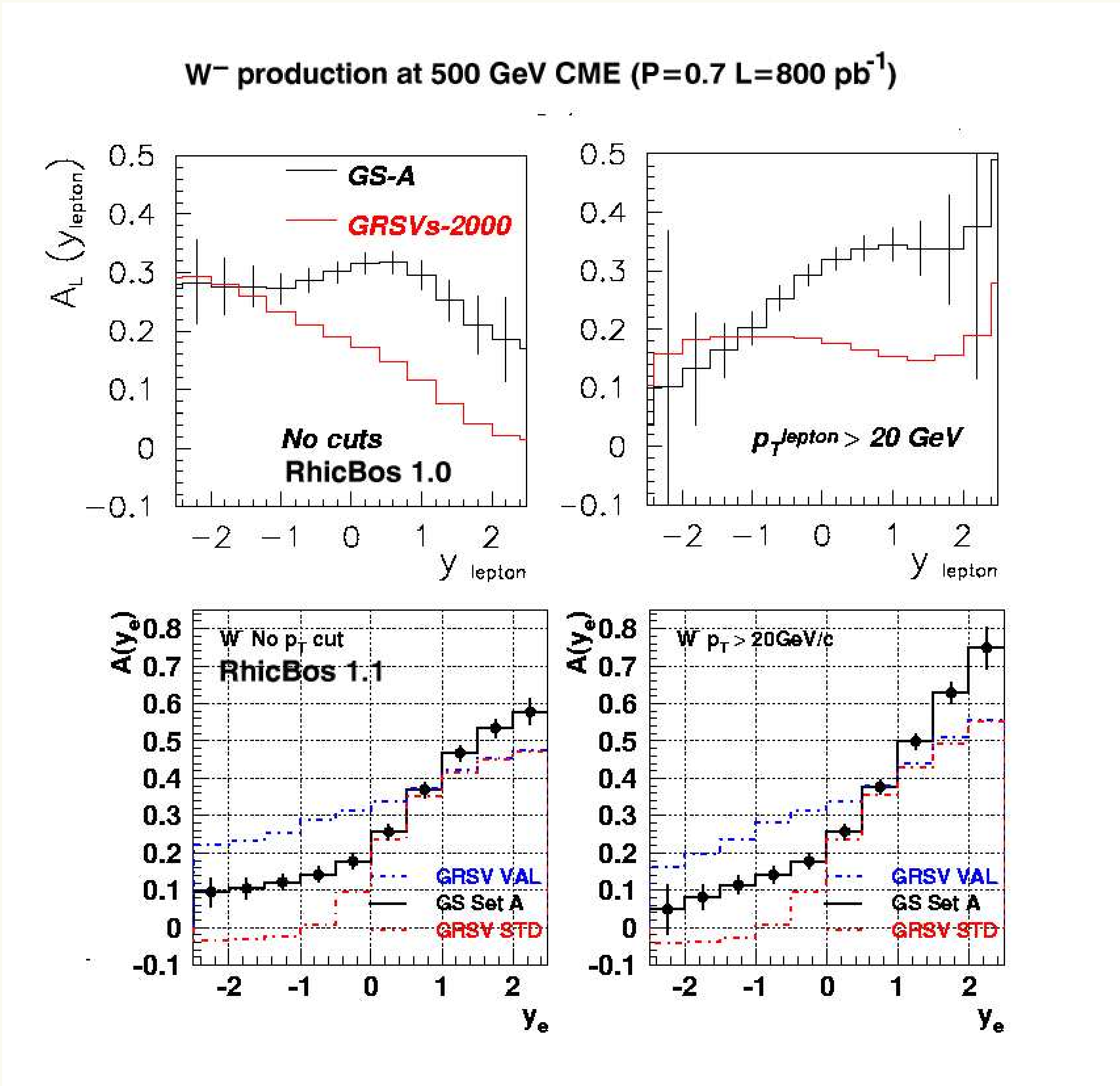
- Updated luminosity ($\mathcal{L} = 400$ pb^{-1} and $\mathcal{L} = 800$ pb^{-1} at $\sqrt{s} = 500$ GeV) and experimental binning

- Comparison vs. Pythia
  ☹ revealed a bug in RhicBos (wrong sign in front of $\cos\theta$ for W^- production)
  ☺ fixed in the version 1.1, available at
  http://hep.pa.msu.edu/~nadolsky/RhicBos/

- A large part of the difference is the sign change for y_{e^-} in $pp \to W^-$ (⇒Fig.)

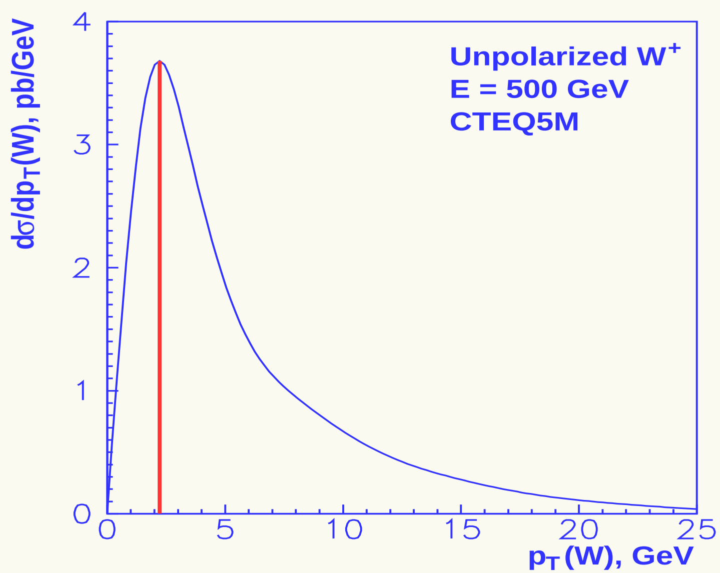


W+ production at 500 GeV CME (P=0.7 L=800 pb-1)
No cuts
RhicBos 1.0
A_L (y_lepton)
y lepton
p_T^lepton > 20 GeV
GS-A
GRSVs-2000
W+ No p_T cut
GRSV VAL
GS Set A
GRSV STD
RhicBos 1.1
A(y_e)
y_e
W+ p_T > 20GeV/c


W⁻ production at 500 GeV CME (P=0.7 L=800 pb⁻¹)
GS-A
GRSVs-2000
No cuts
RhicBos 1.0
$A_L\ (y_{lepton})$
y_{lepton}
p_T^{lepton} > 20 GeV
$A(y_e)$
W No p_T cut
RhicBos 1.1
W p_T > 20GeV/c
GRSV VAL
GS Set A
GRSV STD
y_e

New opportunities at RHIC (part 1)

- p_T distributions in unpolarized and polarized $pp \xrightarrow{\gamma^*} \mu^+\mu^- X$
  - precision test of universality of k_T factorization (Collins-Soper-Sterman resummation)



$q_T \neq 0$! The shape of $d\sigma/dq_T$ at $q_T \to 0$ cannot be described at a finite order of PQCD: calculation of the sum

$$\frac{1}{q_T^2}\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n \sum_{m=0}^{2n-1} v_{mn}\left(\ln^m \frac{Q^2}{q_T^2} \quad \text{or} \quad \delta(\vec{q}_{TW})\right)$$

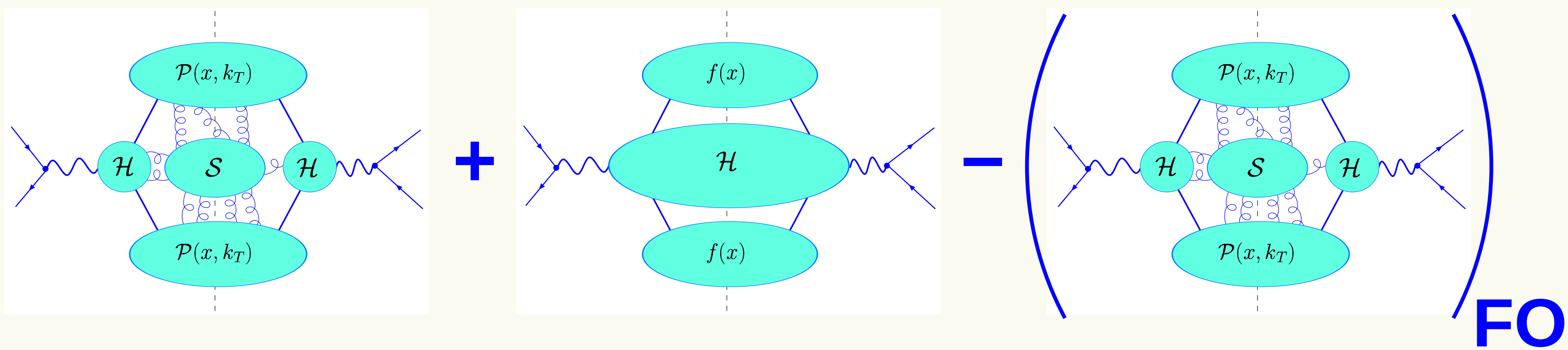
is needed

- k_T factorization in impact parameter (b) space
  (Collins, Soper, Sterman, 1985)

  - proved by a factorization theorem
    (J. Collins, A. Metz, 2004; X. Ji, J.-P. Ma, F. Yuan, 2004)

  - applies to Drell-Yan-like processes, SIDIS, and e^+e^- hadroproduction

  - resummed $d\sigma/dq_T$ are given by products of universal functions with perturbative and nonperturbative components



If universality holds:

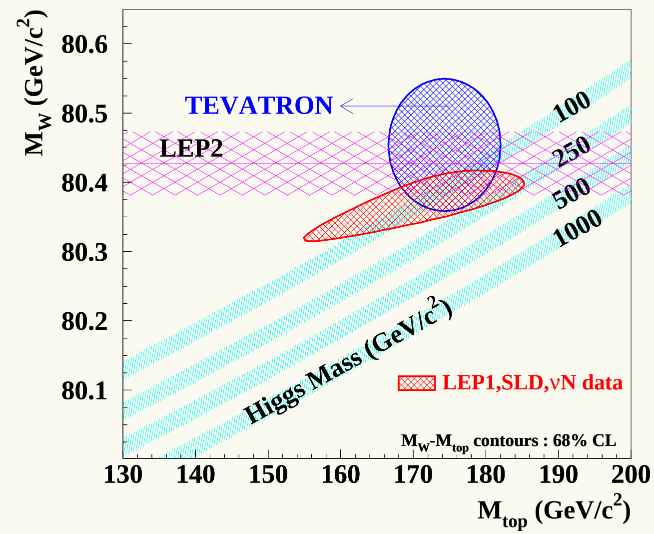
- parts of the resummed $d\sigma/dq_T$ can be "measured" in one set of processes and used to predict other processes
  - global fit of q_T data is feasible
  - for instance, the low-Q Drell-Yan process at RHIC can constrain predictions for W, Z, $\gamma\gamma$, Z',... production at the Tevatron and LHC
    - reduce theory error in the measurement of M_W at the Tevatron and LHC

Measurement of W-boson mass M_W and width Γ_W at the Tevatron
$(p\bar{p} \to WX \to l\nu X)$

Important precision test of the standard model

Combined CDF & DØ Run-1 result:

$$M_W = 80.456 \pm 0.059 \text{ GeV}$$
$$\left(\delta M_W / M_W = 0.0007\right)$$
$$\Gamma_W = 2.115 \pm 0.105 \text{ GeV}$$
$$\left(\delta \Gamma_W / \Gamma_W = 0.05\right)$$



Run-2 goal: reduce δM_W to 30 MeV per experiment
(LHC: $\delta M_W \sim 15$ MeV)

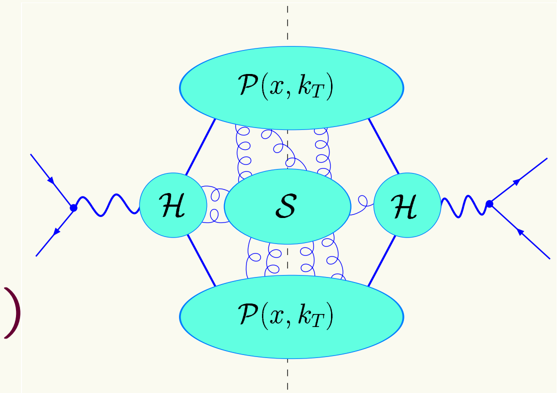
Uncertainties in $d\sigma/dq_T$ is a leading systematical error in M_W

Universality of CSS resummation in the global q_T fit

(A. Konychev, P. N., hep-ph/0506225)

$$\left.\frac{d\sigma}{dQ^2 dy dq_T^2}\right|_{q_T^2 \ll Q^2} = \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \widetilde{W}(b, Q, x_A, x_B)$$

$$\left.\widetilde{W}(b, Q)\right|_{all\ b} \approx \widetilde{W}_{pert}(b_*, Q) e^{-\mathcal{F}_{NP}(b,Q)}$$



- The perturbative term $\widetilde{W}_{pert}$ depends on $b_* \equiv b/(1 + b^2/b_{max}^2)$, with $b_{max} \approx 1$ GeV^{-1}

$$\mathcal{F}_{NP}(b, Q) = \mathcal{F}_S(b, Q) + \mathcal{F}_P(b, x_A) + \mathcal{F}_P(b, x_B)$$

Renormalon analysis *(Korchemsky, Sterman)* suggests that

$\mathcal{F}_S(b, Q) \approx b^2 \{a_1 + a_2 \ln Q\} \oplus$ smaller corrections

- A lattice QCD estimate gives $a_2 = 0.19^{+0.12}_{-0.09}$ GeV^2 *(Tafat)*; a_2 is the same in Drell-Yan, SIDIS and e^+e^- hadroproduction; arises from the soft (Sudakov) factor and is spin-independent
- $\sqrt{s}$ dependence may arise from $\mathcal{F}_P(x, b)$ ($x_{A,B} = Q/\sqrt{s}e^{\pm y}$)

Comparison with fixed-target Drell-Yan and Tevatron Z data

- Renormalon analysis

$$\mathcal{F}_{NP}(b,Q) \approx b^2 \left\{ a_1 + 0.19 \ln\left(\frac{Q}{Q_0}\right) \right\} \equiv a(Q) b^2$$

- A global q_T fit *(Brock, Landry, P. N., Yuan, 2002)*
  - b_* model with $b_{max} = 0.5$ GeV^{-1}: $\widetilde{W}'_{pert}(b) \rightarrow \widetilde{W}_{pert}(b_{max})$ at $b \gg b_{max}$

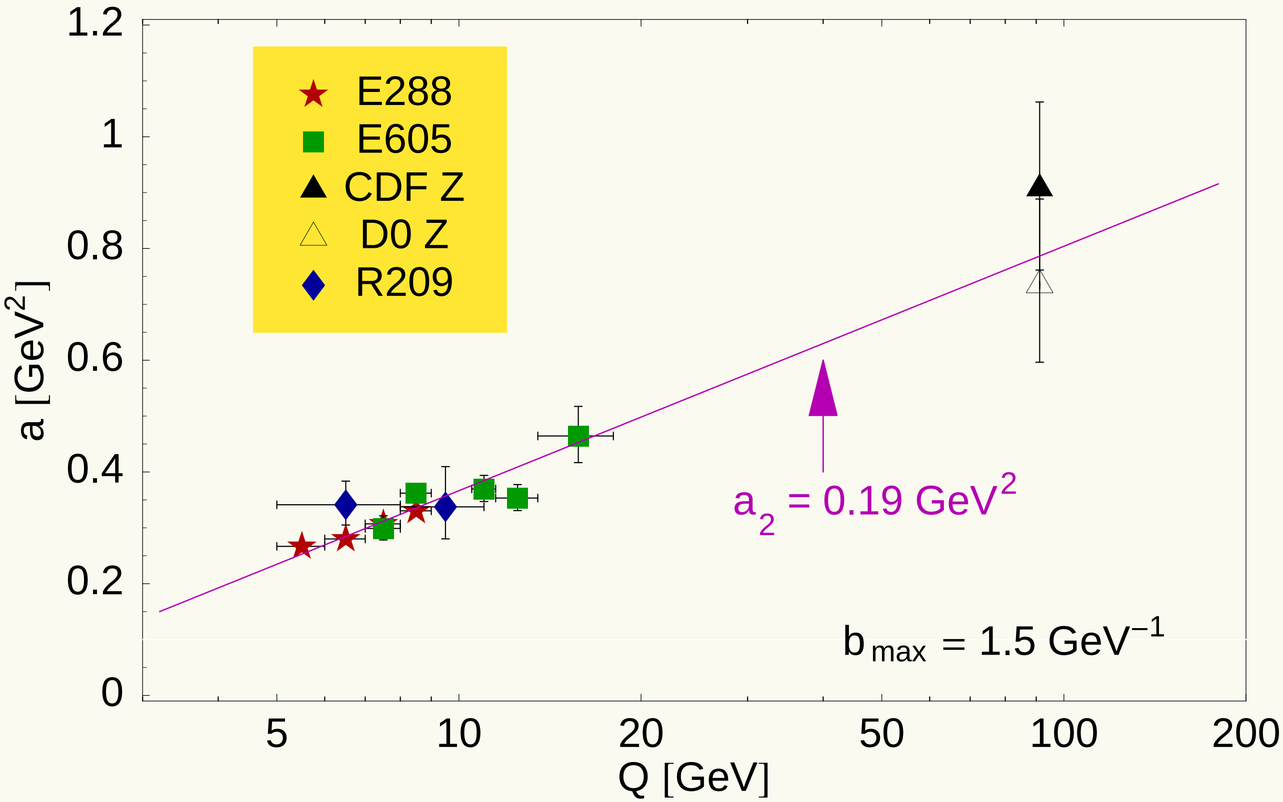
$$\mathcal{F}_{NP}(b,Q) = b^2 \left[0.21 + 0.68 \ln\left(\frac{Q}{3.2\ \mathrm{GeV}}\right) - 0.13 \ln(\underbrace{100 x_A x_B}_{100Q^2/s}) \right]$$

  - $a(M_Z) \sim \langle k_T^2 \rangle / 2 \approx 2.7$ GeV^2

- Extrapolation models
(Qiu, Zhang; Kulesza, Sterman, Vogelsang)
  - $\widetilde{W}'_{pert}(b)\Big|_{b>b_{max}} = \left(\text{extrapolated } \widetilde{W}_{pert}(b)\Big|_{b \leq b_{max}} \right)$
  - $a(M_Z) \approx 0.8$ GeV^2

Which result to believe?

Nonperturbative smearing $a(Q)$: independent scans of 5 experiments at $\sqrt{s} = 27.4 - 1800$ GeV



Revised b_* model

($b_{max} = 1.5$ GeV^{-1})

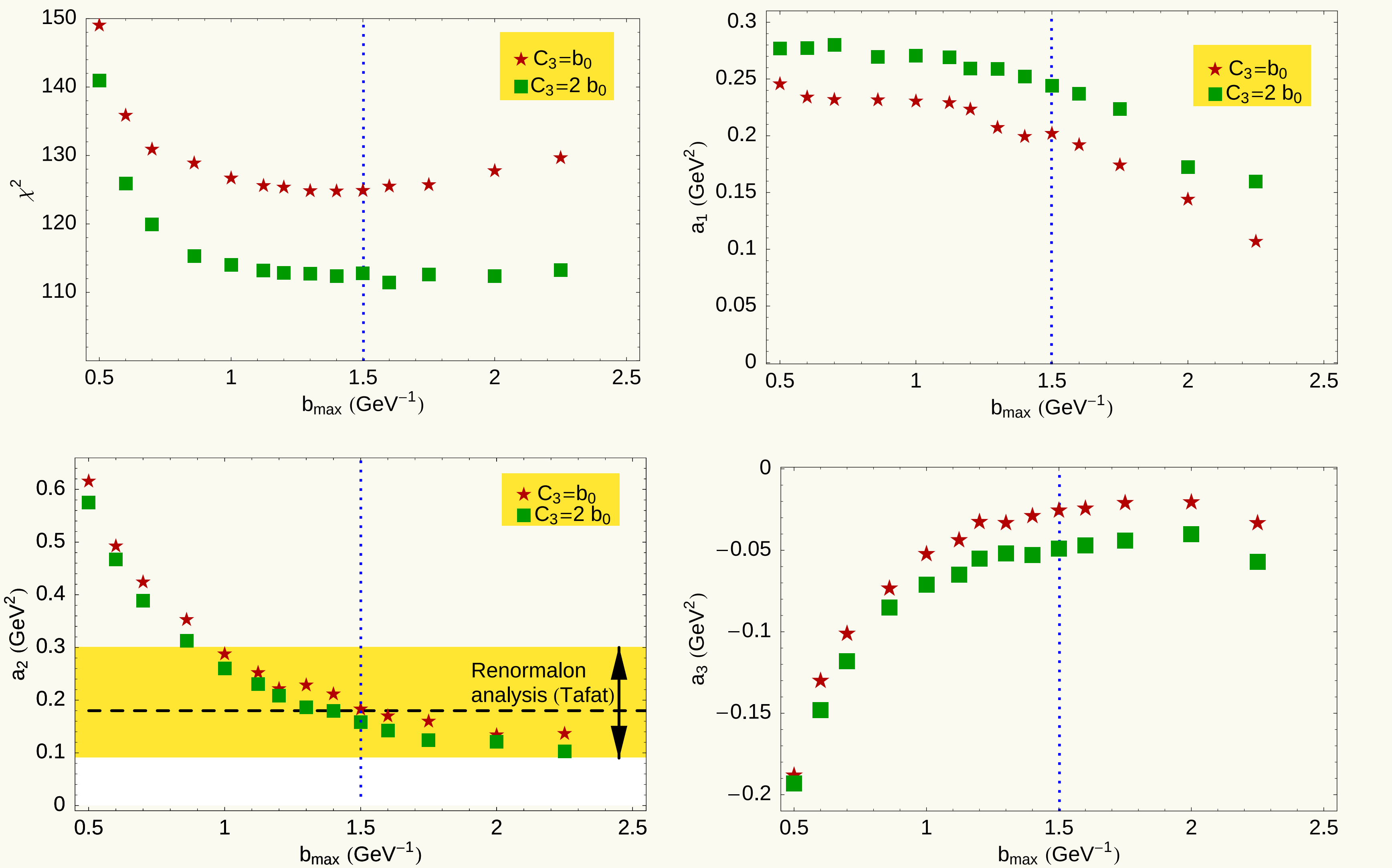
$$\mathcal{F}_{NP}(b,Q) \approx a(Q) b^2,$$

with

$$a \sim \langle k_T^2 \rangle / 2$$

- ❑ The best-fit $a(Q)$ shows quasi-linear dependence on $\ln(Q)$
- ❑ Its energy derivative, $a_2 = da/d(\ln Q) \sim 0.18$ GeV^2, agrees well with the lattice QCD estimate, $(a_2)_{lattice} = 0.19^{+0.12}_{-0.09}$ GeV^2

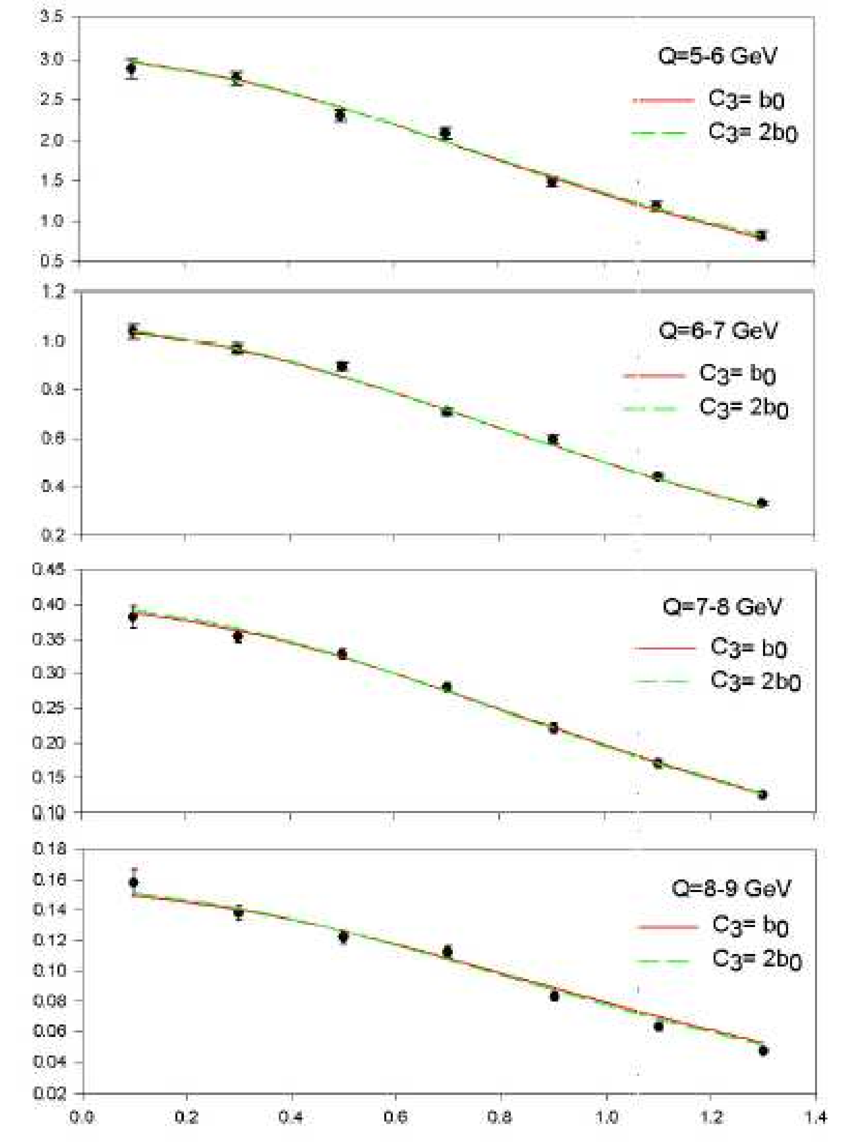
Global fit in the revised b_* prescription: scan over b_{max}



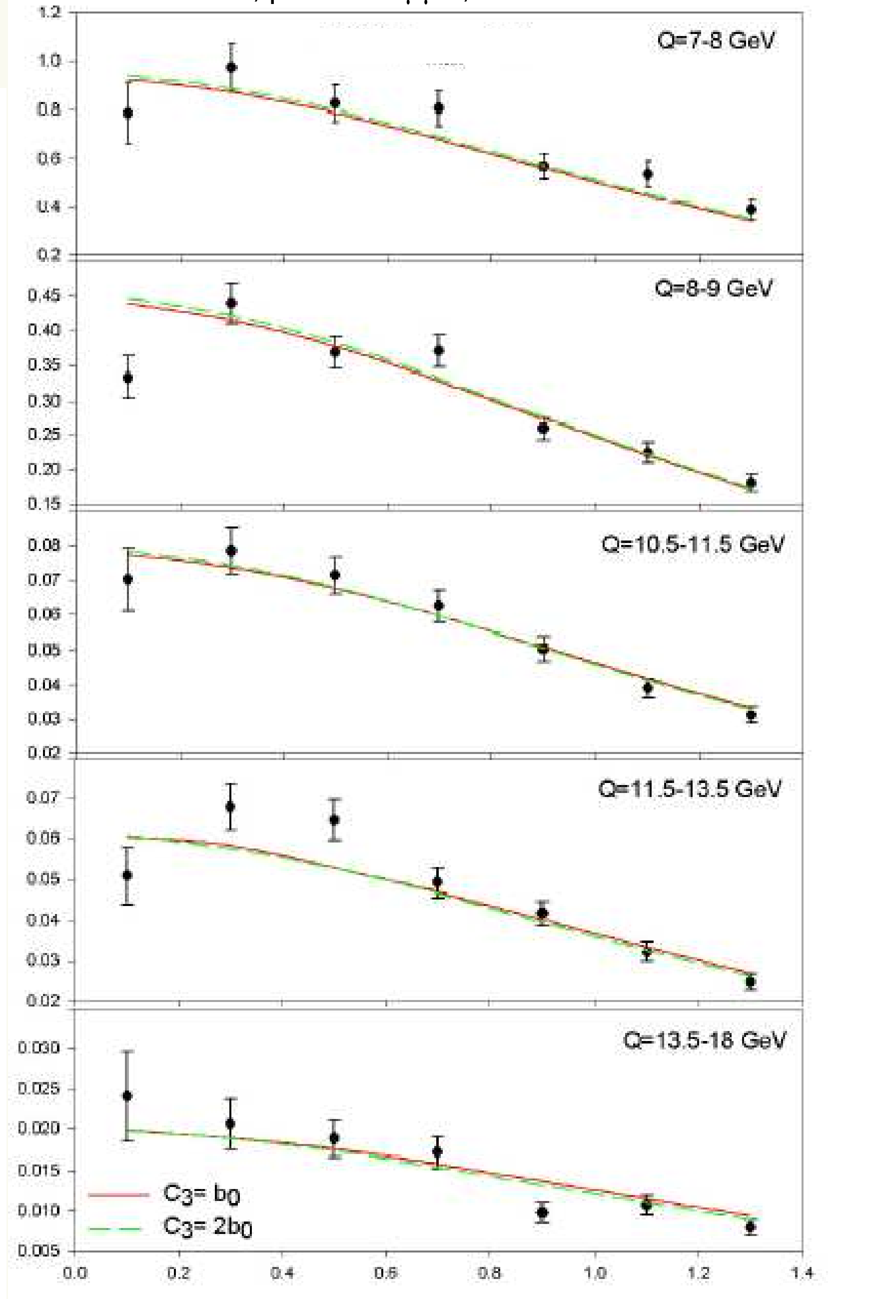
Best fit: $b_{max} \approx 1.5$ GeV^{-1}, $\beta \approx -0.4 - 0.3$ (set to 0), $a_1 \approx 0.23$, $a_2 \approx 0.18$, $a_3 \approx -0.05$

- The new fit supports dominance of soft contributions in $\mathcal{F}_{NP}(b,Q)$
  - Gaussian $\mathcal{F}_{NP}(b,Q) = b^2\left[0.20 + 0.19\ln(Q/3.2) - 0.026\ln(100x_A x_B)\right]$
  - linear $\ln Q$ dependence
  - small $\sqrt{s}$ dependence
  - no flavor dependence
- Drell-Yan q_T data from RHIC can
  - test $\mathcal{F}_{NP}(b,Q)$ at intermediate $\sqrt{s} = 200$ or 500 GeV
  - resolve remaining tensions between the experiments
  - test spin independence of $\mathcal{F}_{NP}(b,Q)$

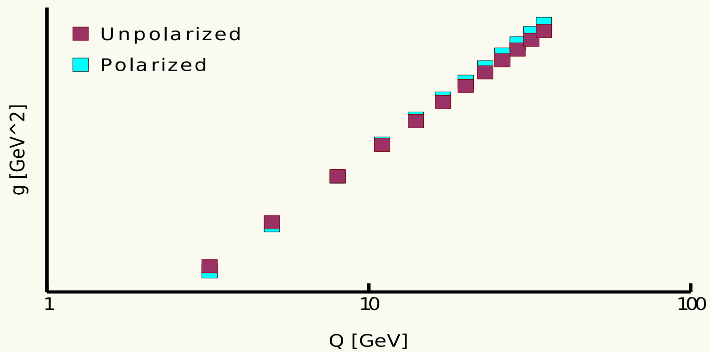
E288, p + Cu -> $\mu\bar{\mu}$X, ECM = 27.4 GeV



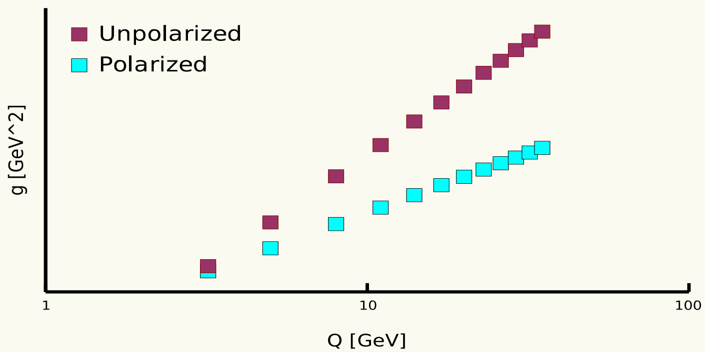
E605, p + Cu -> $\mu\bar{\mu}$X, ECM = 38.8 GeV



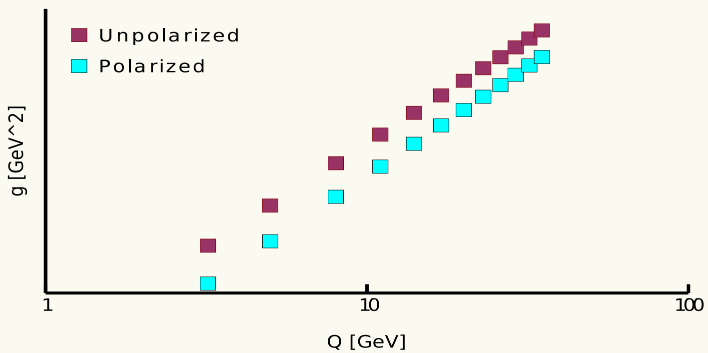
Spin (in)dependence of k_T smearing



Universal kT smearing



Spin-dependent Sudakov factor



Spin dependence from the unintegrated PDF's and/or Sudakov factor

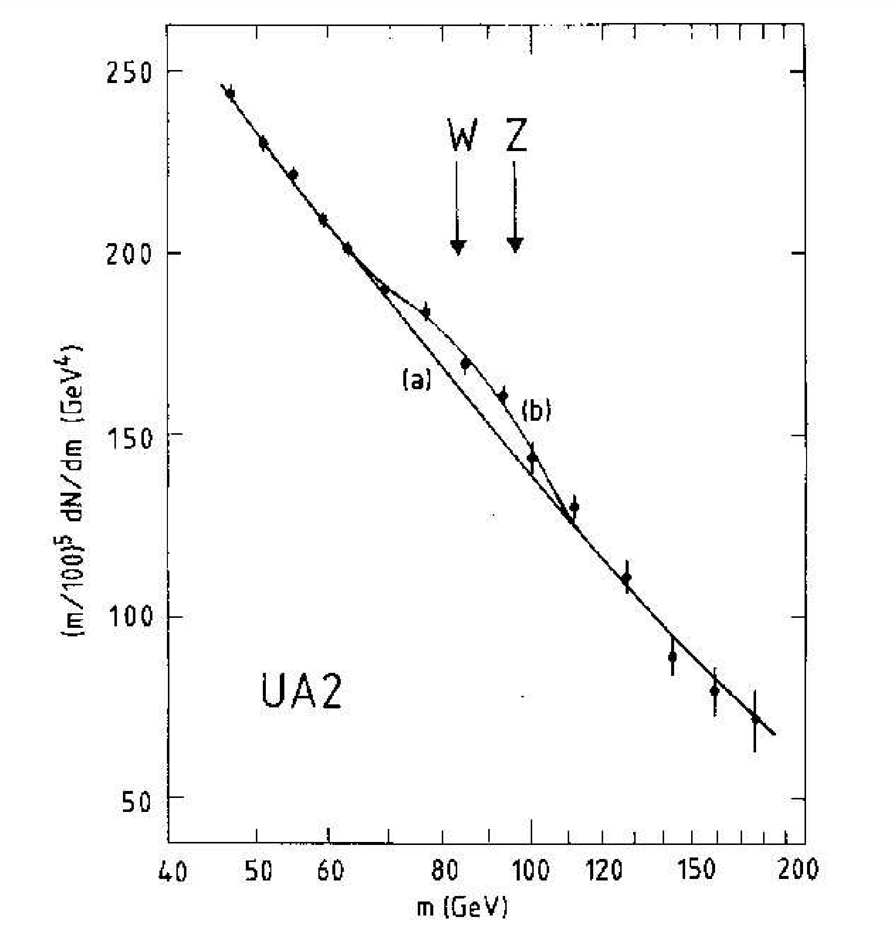
New opportunities at RHIC (part 2): hadronic decays of W bosons

- The $W \to e\nu$ decay is the golden mode at large luminosities ($\mathcal{L} > 300$ pb^{-1})

- Hadronic decays may be competitive at RHIC for lower $\mathcal{L} \approx 100$ pb^{-1} and reduced instrumentation (no lepton charge ID)

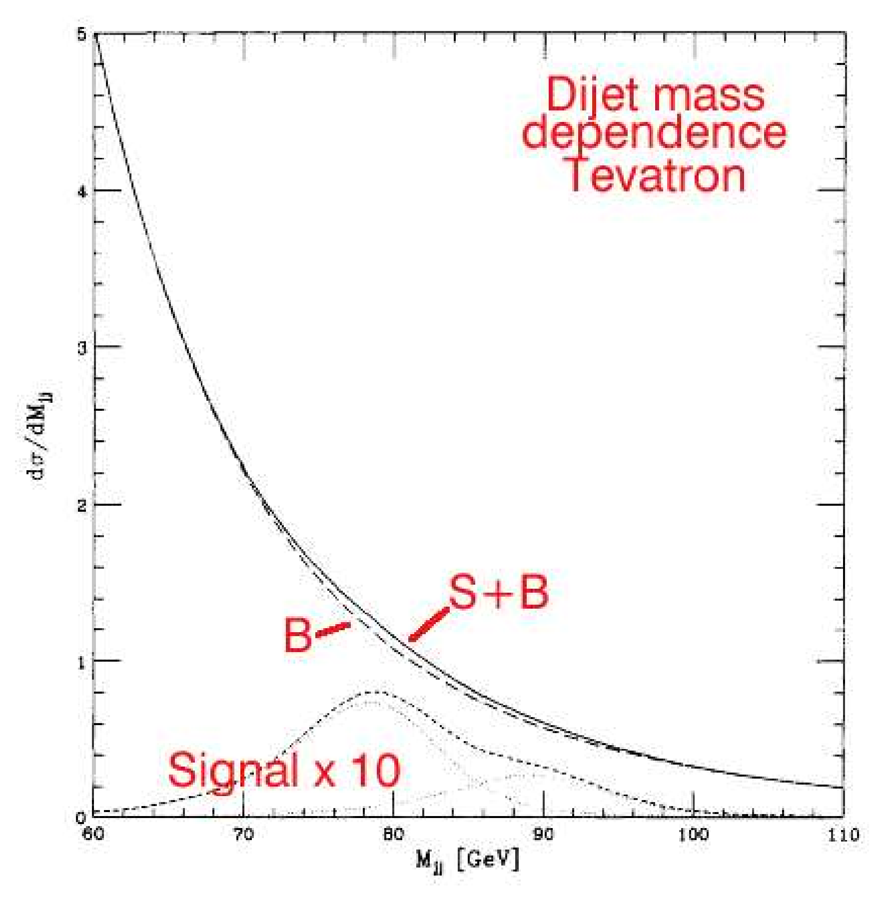
- Hadronic decay mode should be more accessible at RHIC than at the Tevatron or LHC
  - much lower background, especially for parity-violating A_L
  - lower resolution sufficient (it is not the M_W measurement)

$W \to$ hadrons at SPS *(PL, B186, 452 (1987))*



- $p\bar{p} \to WX$, $\sqrt{s} = 630$ GeV, $\mathcal{L} = 0.73\ \mathrm{pb}^{-1}$; $x \sim 0.13$
- 3σ signal in the dijet mass (m) distribution
- background/signal≈ 20
- background is smooth
  - can be extrapolated from the sidebands
- Mass resolution $\delta m = 8 - 9$ GeV
- W and Z peaks are not separated

$W \to$ hadrons at Tevatron *(J. Pumplin, PRD45, 806 (1992); U. Baur et al., hep-ph/0005226)*



- $p\bar{p} \to WX$, $\sqrt{s} = 1.8$ TeV, $x \sim 0.04$
- background/signal$\approx$ 570
- After an angular cut in the W rest frame: background/signal$\approx$255 $QQ/W \approx 22$, $QG/W \approx 101$, $GG/W \approx 132$
- mass resolution $\delta M_{jj} \geq 0.5$ GeV
- of no use for M_W measurement, unless the gluon background is drastically reduced

Hadronic decays: RHIC vs. SPS and Tevatron

☺ smaller $\sqrt{s}$ (500 vs. 630 and 1800 GeV): gluon background $\downarrow$

☹ pp vs. $p\bar{p}$: gluon background $\uparrow$

$\Rightarrow$ background/signal$\approx$20 for σ_L;

≈ 0 for $\Delta_L^{PV}\sigma$ (false asymmetry only!)

☺ the background can be extrapolated from the sidebands

Hadronic vs. leptonic decays

☺ Larger cross sections: Br($W \to q_i \bar{q}_j$)/Br($W \to e\nu$) ≈ 6

☺ Direct measurement of $d\sigma/dy_W$ possible

☺ Symmetry between the jets
$\Rightarrow$ smaller dependence on the acceptance

☹ Energy & mass resolution$\approx$ 10 GeV; no charge ID
W^+, W^- and Z^0 cannot be separated

☹ Increased Z^0 contamination:

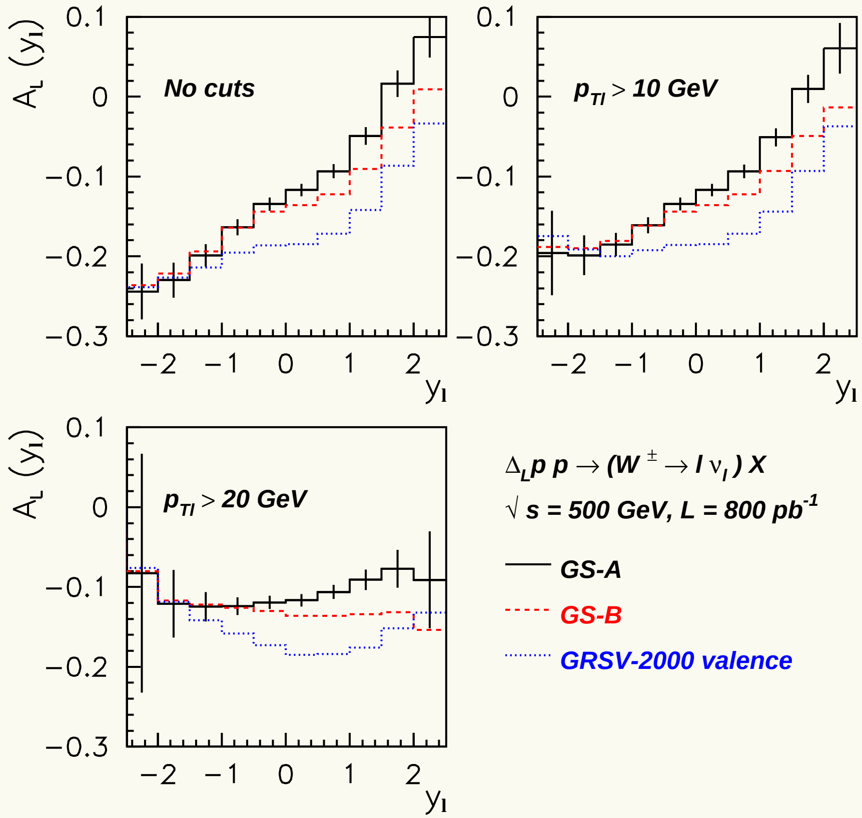
Br(Z$\to q\bar{q}$)/Br($Z \to e^+e^-$) ≈ 20

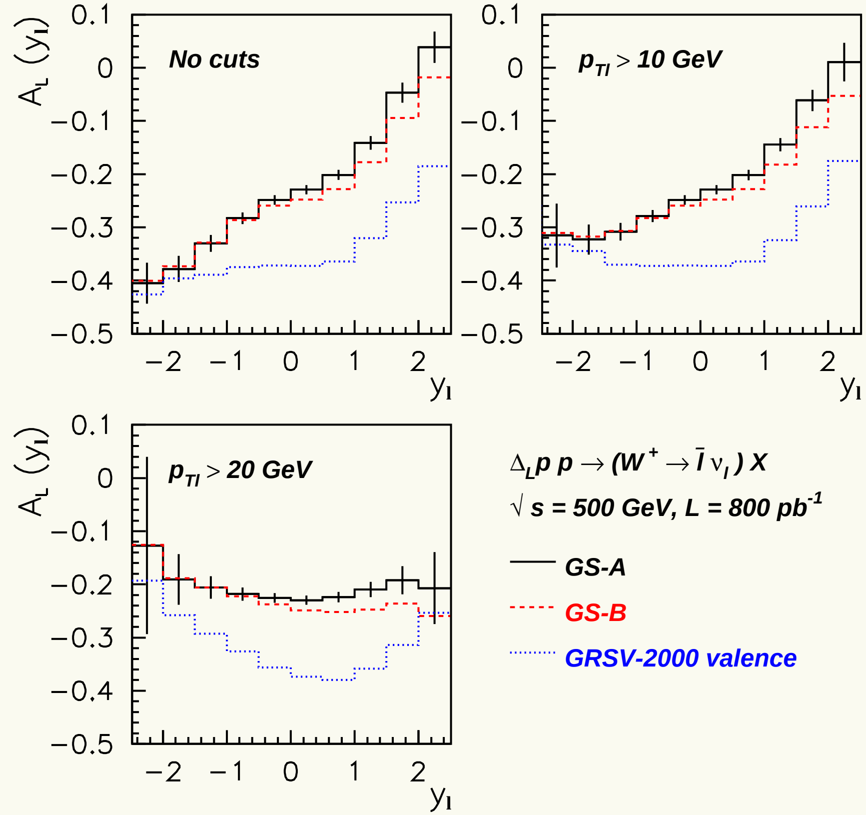
leptonic decays: $\sigma_{W^+} : \sigma_{W^-} : \sigma_{Z^0} = 1 : 0.33 : 0.08$

hadronic decays: $\sigma_{W^+} : \sigma_{W^-} : \sigma_{Z^0} = 1 : 0.33 : 0.26$

☺ The Z^0 component can be reduced by reweighting M_{jj} bins

Combined $W^{\pm}$ sample (left) vs. W^{+} sample (right) for $W \to e\nu$

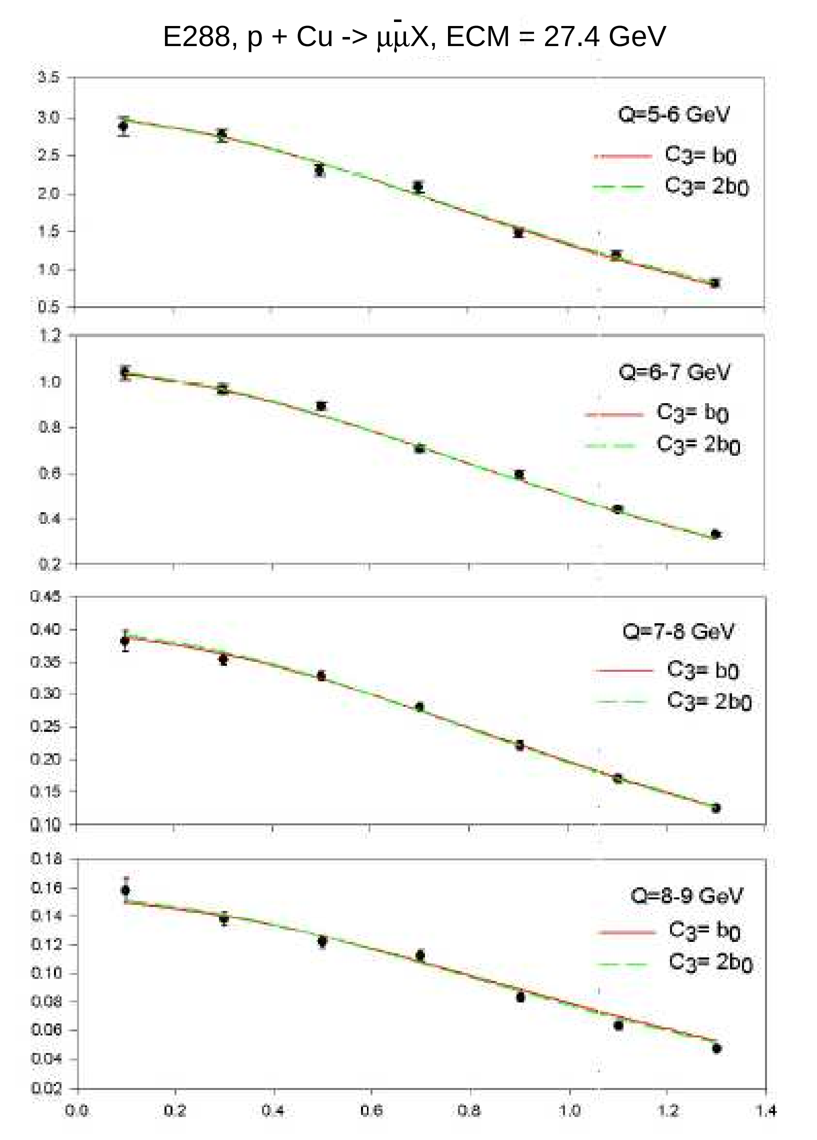


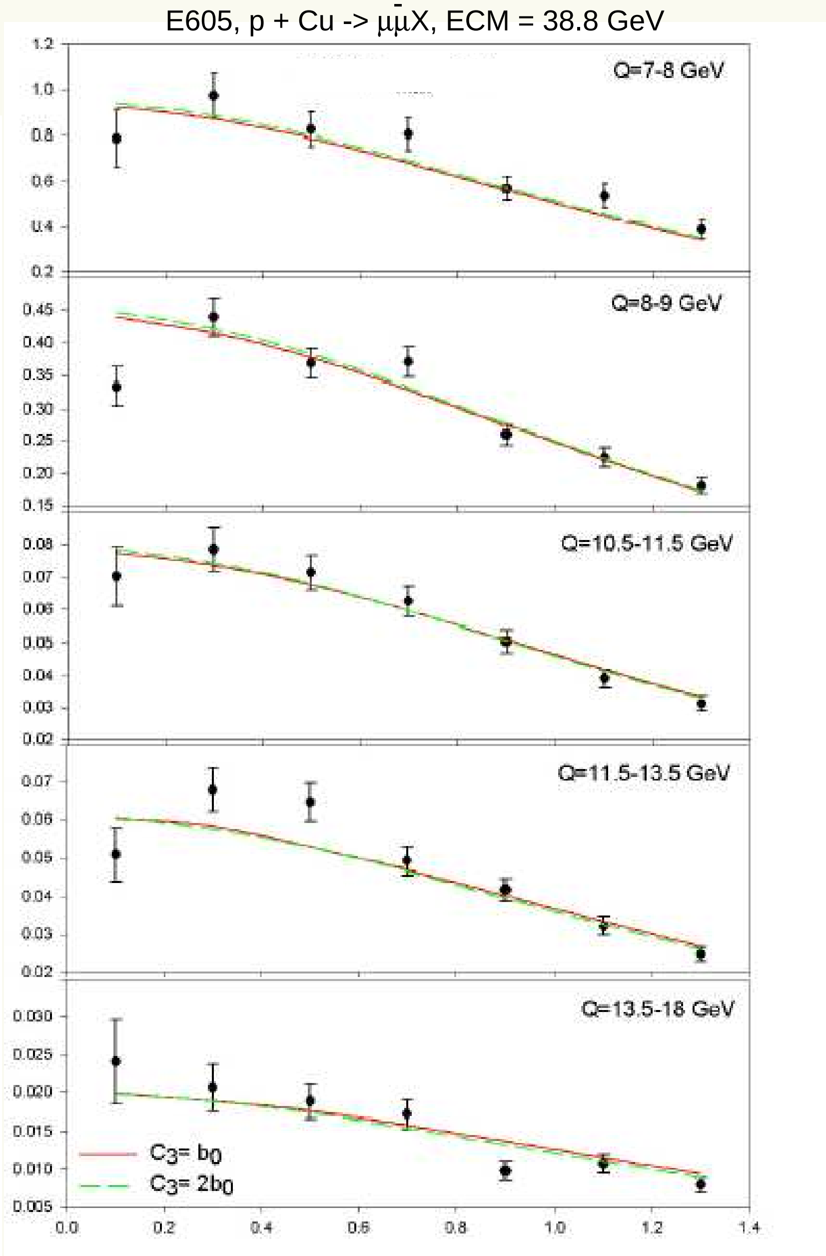


Summary

- High quality of the global q_T fits supports universality of the non-perturbative contributions $\mathcal{F}_{NP}(b,Q)$ in unpolarized Drell-Yan-like processes
- Future RHIC low-Q Drell-Yan q_T data can further constrain $\mathcal{F}_{NP}(b,Q)$ and test its spin independence
  - what are the plausible experimental parameters for such a measurement?
- Potential for the measurement of A_L^{PV} in hadronic W decay channels is promising at low $\mathcal{L}$; can be investigated as a contribution to this workshop

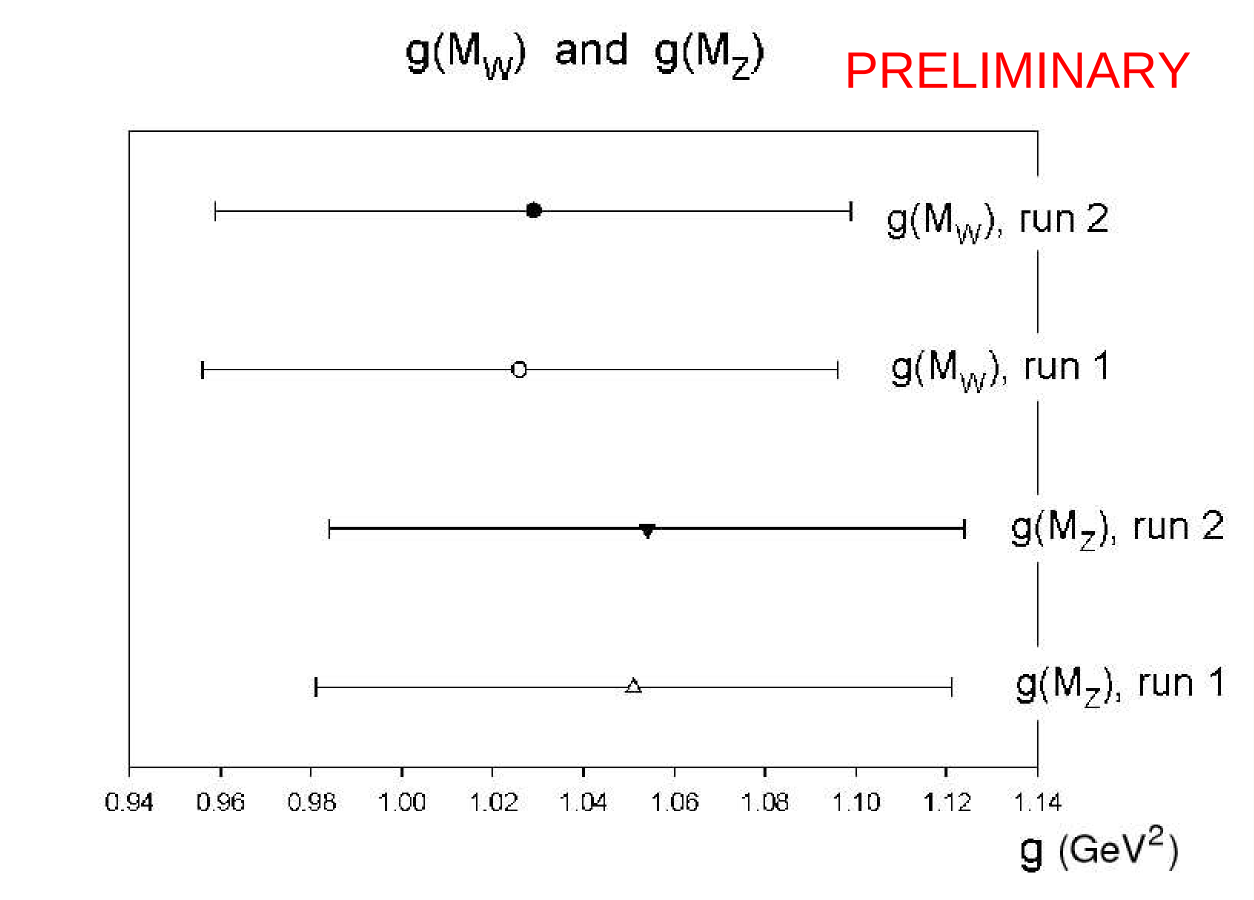
Backup slides


E288, p + Cu -> μμ̄X, ECM = 27.4 GeV
Q=5-6 GeV
C3= b0
C3= 2b0
Q=6-7 GeV
C3= b0
C3= 2b0
Q=7-8 GeV
C3= b0
C3= 2b0
Q=8-9 GeV
C3= b0
C3= 2b0


E605, p + Cu -> μμ̄X, ECM = 38.8 GeV
Q=7-8 GeV
Q=8-9 GeV
Q=10.5-11.5 GeV
Q=11.5-13.5 GeV
Q=13.5-18 GeV
C3= b0
C3= 2b0

Experimental uncertainties: $a(Q)$ at $Q = M_W$ and $Q = M_Z$ for $b_{max} = 1.2$ GeV^{-1}

- Obtained using a Lagrange multiplier method



- Errors are for $\delta\chi^2_{tot} = 1$

A preliminary fit: $g(Q) = a(Q)$

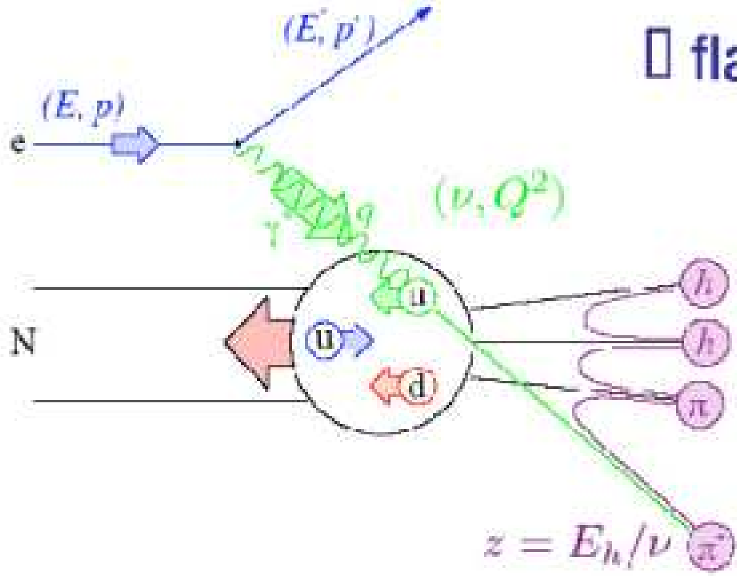
- Translates into a variation $\approx \pm 50$ MeV in the peak of $d\sigma(W)/dq_T$

Summary

- q_T resummation in b-space has excellent predictive power
- Recent developments in q_T resummation include
  - a model for large-b contributions in Drell-Yan-like processes
    - the 2005 fit prefers a universal 2-parameter Gaussian non-perturbative function $S_{NP}(b,Q)$, with $\ln Q$ dependence in a quantitative agreement with lattice QCD
  - study of energy (x) dependence of resummed cross sections
    - If broadening of $d\sigma/dq_T$ is observed in forward Z boson (Drell-Yan pair) production in the Tevatron Run-2, it will strongly affect predictions for W and Z production at the LHC
  - New method (CSS+ACOT) for three-scale resummation (q_T, Q, M) in heavy flavor production
    - quantitative evaluation of mass effects in production of heavy flavors, W, SUSY Higgs bosons, etc.

Backup slides

Polarized semi-inclusive DIS



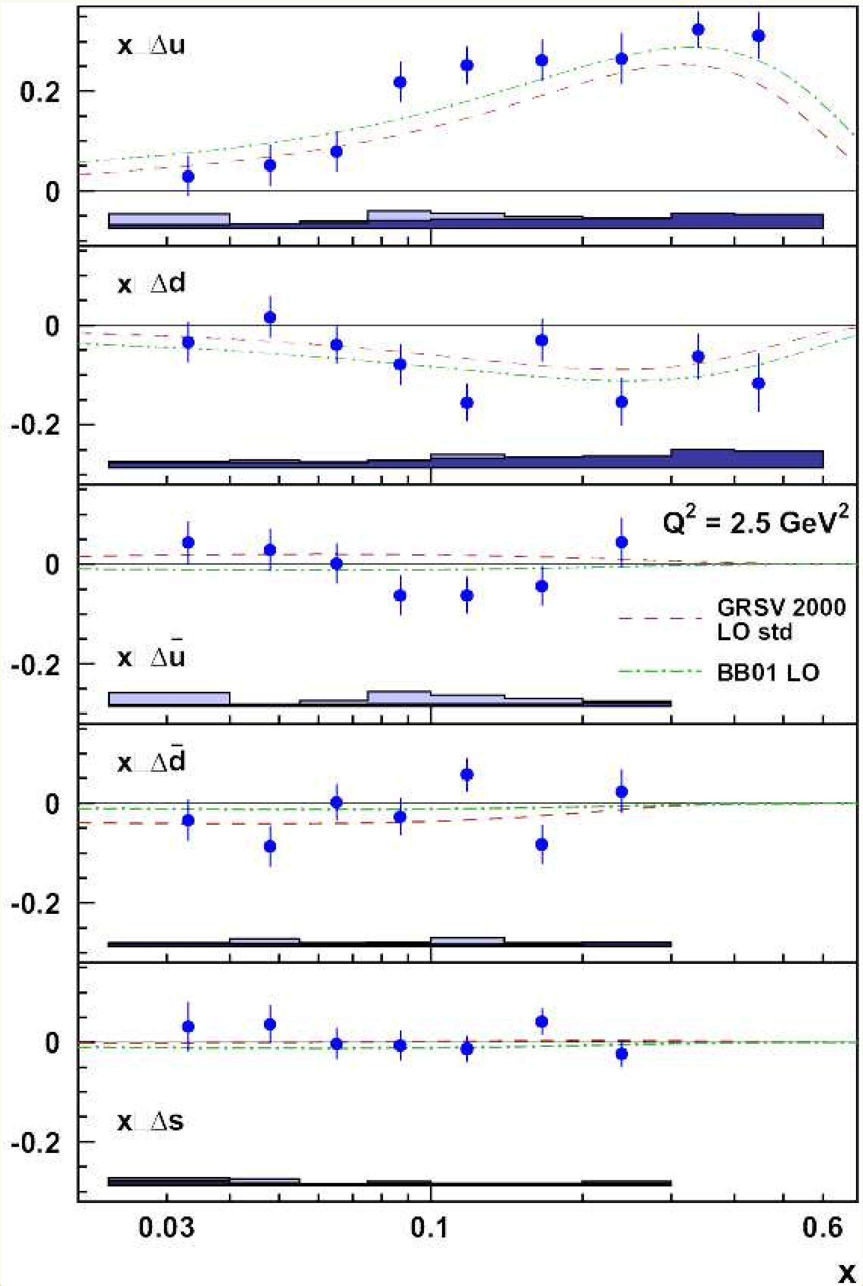
 flavour separation by flavour tagging

flavour content of final state hadrons related to flavour of struck quark via *fragmentation functions*

$$A_1^h(x,Q^2) = \frac{{}^{h}_{1/2} - {}^{h}_{3/2}}{{}^{h}_{1/2} + {}^{h}_{3/2}} \approx \frac{\sum_q e_q^2\, q\ (x,Q^2) \int dz\, D_q^h(z,Q^2)}{\sum_q e_q^2\, q\ (x,Q^2) \int dz\, D_q^h(z,Q^2)}$$

Born-level analysis
Fragmentation contributes constant factors

SIDIS at HERMES, COMPASS, and JLab



$\frac{\Delta u(x)}{u(x)}, \frac{\Delta d(x)}{d(x)}, \frac{\Delta s(x)}{s(x)}, \frac{\Delta \bar{u}(x)}{\bar{u}(x)}, \frac{\Delta \bar{d}(x)}{\bar{d}(x)}$

Born-level analysis

- may be OK for $\Delta u(x)/u(x)$, $\Delta d(x)/d(x)$

  + helicity conversation in PQCD radiation off valence quarks

  – unreliable at low Q

  – wrong kinematics

- probably not OK for $\Delta \bar{q}(x)/\bar{q}(x)$

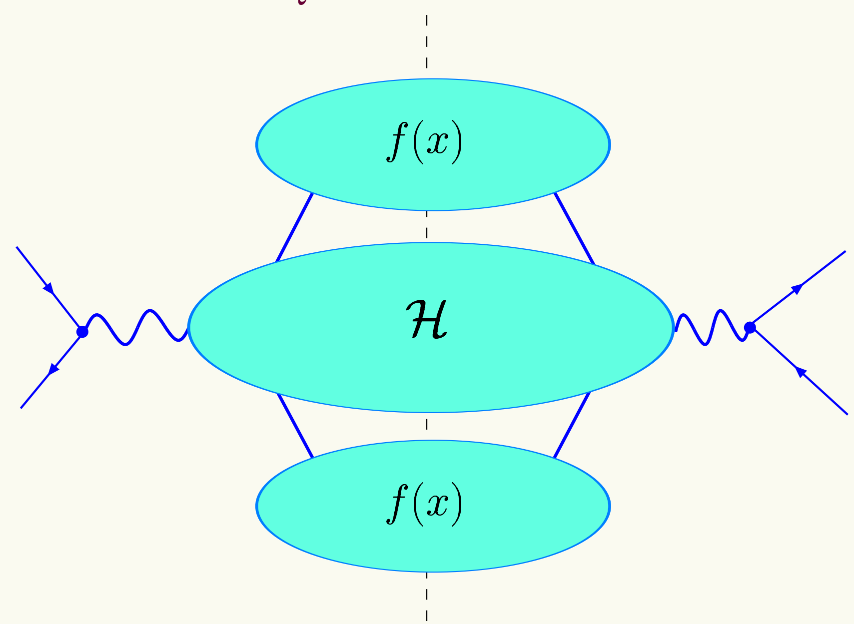
– dependence on the fragmentation model

– power-suppressed terms?

QCD factorization in hard and soft regions

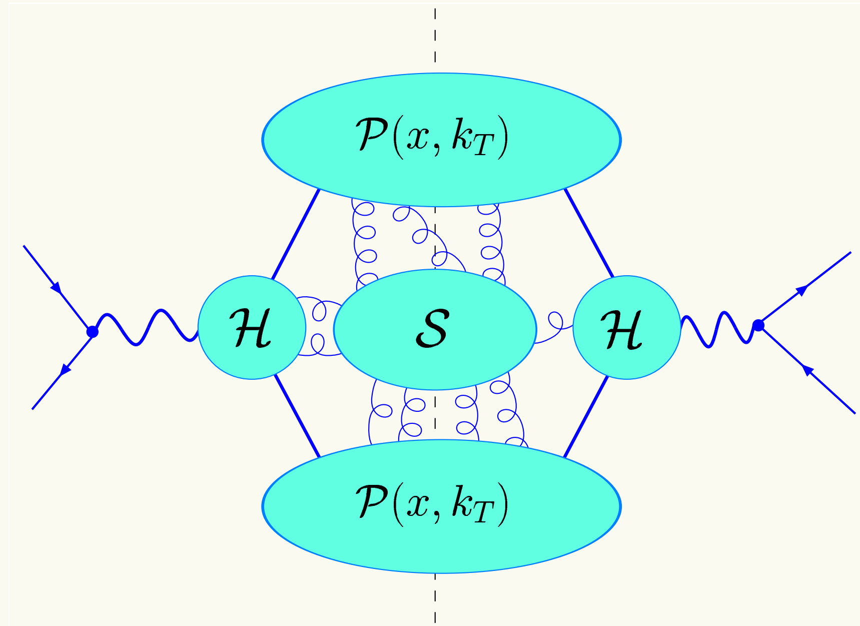
Finite-order (FO) factorization

$\Lambda^2_{QCD} \ll q_T^2 \sim Q^2$



Small-q_T factorization

$\Lambda^2_{QCD} \ll q_T^2 \ll Q^2$



Solution for all q_T: